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INTERACTIONS BETWEEN ATTENTION AND WORKING MEMORY

E. AWH,* E. K. VOGEL AND S.-H. OH

University of Oregon, Eugene, OR 97403, USA

Abstract—Studies of attention and working memory address the fundamental limits in our ability to encode and maintain behaviorally relevant information, processes that are critical for goal-driven processing. Here we review our current understanding of the interactions between these processes, with a focus on how each construct encompasses a variety of dissociable phenomena. Attention facilitates target processing during both perceptual and postperceptual stages of processing, and functionally dissociated processes have been implicated in the maintenance of different kinds of information in working memory. Thus, although it is clear that these processes are closely intertwined, the nature of these interactions depends upon the specific variety of attention or working memory that is considered. © 2005 Published by Elsevier Ltd on behalf of IBRO.

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In most cases, studies of attention and working memory have emphasized qualitatively different limitations in processing. Models of working memory highlight the temporary *maintenance* of information in a limited-capacity system that promotes efficient access and updating. Models of selective attention, by contrast, emphasize the efficient *encoding* of relevant targets in spite of a potentially overwhelming quantity of sensory information. These two constructs have been dominant in the field of cognitive neuroscience, and significant theoretical development has occurred through independent studies of these processes. Nevertheless, it is clear that the continued development of research in these domains must include clear models of how these processes interact with one another. For example, Cowan (1995) offers the view that the contents of working memory are best understood as "activated" representations from within long term memory that are currently within the focus of attention. By this view, the very definitions of attention and working memory are closely intertwined. Indeed, consideration of the two constructs reveals clear overlap in information processing goals. Both processes enable goal-driven processing by increasing the accessibility of relevant over irrelevant information. Moreover, targeted empirical studies have revealed functional overlap between these systems that goes beyond these conceptual links.

*Corresponding author. Tel: +1-541-346-4983; fax: +1-541-346-4911.
E-mail address: awh@uoregon.edu (E. Awh).

Abbreviations: AB, attentional blink; ERP, event-related potential; fMRI, functional magnetic resonance imaging; LIP, lateral intraparietal sulcus; SOA, stimulus onset asynchrony.

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One approach that has yielded important insights into the links between attention and working memory has focused on individual differences in working memory capacity and controlled attention (e.g. Engle et al., 1999; Kane et al., 2001; Cowan, 1995). These investigations examine the simple prediction that strong links between selective attention and working memory will lead to significant associations between an individual's working memory capacity and their ability to exert top-down control over the encoding of new information. For example, Kane and colleagues (2001) found that an individual's working memory capacity predicted their performance in an anti-saccade task that required an eye movement to the side of space opposite from a visual cue. Low-span subjects were slower and less accurate in the anti-saccade task, a result that suggests a link between the use of controlled attention to suppress the pre-potent tendency to look toward the visual cue, and the successful storage of information within working memory. Thus, correlations between capacity in working memory and the efficiency of controlled attention reveal links between the two constructs.

One challenge for interpreting such data, however, is that neither attention nor working memory is implemented in a unitary fashion. A wide variety of research has demonstrated that attention can influence processing during both early sensory and postperceptual stages of processing (for one review, see Luck and Hillyard, 1999). For example, a recent study demonstrated both early and late selection effects within a single procedure that measured spatial selection effects (Vogel et al., in press), while manipulating the stimulus onset asynchrony (SOA) between the cue and target When a greater load was imposed on early perceptual analysis of the target (i.e. short SOAs), early selection effects were observed. When the processing bottleneck shifted to the process of transferring perceptual representations into working memory (i.e. long SOAs), late selection effects were observed. Thus, both early and late selection effects can be observed, with the locus of attentional selection determined in part by the specific stages of processing where target processing is difficult (see also the *perceptual load hypothesis*; Lavie (1995).

Just as there are clear indications of different kinds of attentional selection, behavioral and biological evidence strongly suggests functionally dissociated mechanisms for the maintenance of different kinds of information in working memory (e.g. Baddeley, 1986; Smith and Jonides, 1999). Thus, the effort to understand the interactions between these processes may benefit from a detailed analysis of which variety of attention and working memory is being measured. In line with this point, we have endeavored to organize our discussion of "attention" effects by virtue of the specific stages of processing that are modulated by attention in a given paradigm. Likewise, the conclusions will sometimes differ depending on the kind of working memory system that is implicated. In this case, we have focused on paradigms that involve the maintenance of spatial and object information in working memory. Although there is a rich literature examining working memory for verbal information, the interactions between attention and working memory have been more thoroughly documented in the visual domain. The overall evidence converges on the conclusion that there are strong dependencies between the processes that enable the storage of information in working memory and top-down control over the encoding of new information. These dependencies are expressed during multiple stages of processing, across a wide range of tasks, and with a variety of information types.

Attentional modulations of sensory encoding

One of the primary debates in early studies of attention concerned the specific stages of processing where selective attention has its effects. According to early selection models, attention acted to filter out irrelevant information during early sensory stages of processing, prior to the full identification and analysis of a stimulus (Broadbent, 1958). By contrast, late selection models suggested that all sensory information was encoded at the outset, and that attention operated by constraining which of these sensory representations would gain access to later stages of processing (Deutsch and Deutsch, 1963). As we have already suggested, however, this simple dichotomy is an oversimplification. It is now clear that attention operates during both early sensory and postperceptual stages of processing. We begin by reviewing the evidence that demonstrates early selection effects. These data set the stage for the rest of this review, by providing a contrast with attention effects that can be demonstrated at later stages of processing. Furthermore, as we shall see, the same attentional processes that influence these early stages of sensory analysis also play a role in the active maintenance of information within working memory (Awh and Jonides, 2001).

Arguably, the most convincing demonstrations of early selection have come from observations of stimulus-evoked responses within early perceptual processing pathways when the evoking stimulus is attended or unattended (for a review, see Hillyard et al., 1999). For example, studies using event-related potentials (ERPs) have shown that the initial responses evoked within visual cortex are amplified for attended visual stimuli within the first 100 ms of stimulus onset (e.g. Van Voorhis and Hillyard, 1977). Likewise, unit recordings of single cells in the primate visual cortex reveal amplified responses to attended visual stimuli that begin within 60 ms after stimulus onset (e.g. Luck et al., 1997). More recently, neuroimaging studies using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have demonstrated clear attentional modulations within the specific brain regions that mediate perceptual processing for the relevant stimulus attributes (e.g. Corbetta et al., 1990; Heinze et al., 1994). Thus, both the timing and the localization of these attentional modulations provide a strong indication that attention influences some of the earliest stages of perceptual analysis.

Attention as a "gatekeeper" for working memory

Estimates of the capacity of visual working memory suggest that only three to four objects can be maintained simultaneously (Sperling, 1960; Irwin and Andrews, 1996; Luck and Vogel, 1997; Vogel et al., 2001). Thus, goal-directed processing depends on the ability to exert top-down control over which items will occupy this severely limited space. In this sense, attention can serve as a kind of "gatekeeper" for working memory, by biasing the encoding of information toward the items that are most relevant to the current processing goals. The *attentional blink* (AB) paradigm provides a clear demonstration of this form of postperceptual selection. In this procedure, observers are asked to identify and report two visual targets that are presented in rapid succession. Numerous studies have revealed that after the first visual target is identified there is a period of several hundred milliseconds afterward when the processing of subsequent targets is impaired (e.g. Broadbent and Broadbent, 1987; Chun and Potter, 1995; Duncan et al., 1994; Reeves and Sperling, 1986). The prevailing models of this effect assert that the AB is a result of capacity limitations in the formation of durable traces in working memory (Chun and Potter, 1995; Jolicoeur, 1999). By this view, the initial sensory encoding of the second target proceeds without impairment, but the resulting perceptual representation fails to gain access to working memory. This AB effect is consistent with an active process of attentional selection that gives some items a competitive advantage for encoding into working memory. An alternative perspective, however, is that the AB effect simply reveals a bottleneck in the encoding of information into working memory that results in the eventual loss of the second target. Both views are consistent with the data observed, but we note that the effect is instruction-dependent and therefore that target encoding (or lack thereof) is subject to top-down control. For example, if the observer is instructed to ignore the first target, no AB is observed for the second target (Raymond et al., 1992). In our view, this type of goal-driven encoding reveals one aspect of attentional control.

Shapiro et al. (1997a) provide behavioral evidence consistent with a postperceptual model of the AB effect. They found that a subject's own name tends to be resistant to AB interference. The observation that the semantic status of the second target influences the degree of AB interference suggests that semantic analysis must occur for the stimuli presented during the AB period. Along the same lines, studies by Shapiro et al. (1997b) and Maki et al. (1997) revealed significant semantic priming effects from stimuli that were presented during the AB period, again supporting the idea that AB interference does not preclude the semantic analysis of a stimulus. One limitation of these studies, however, is that there was no explicit comparison of the degree of semantic processing that occurred for stimuli inside and outside the AB period. These results therefore leave open the possibility that AB interference leads to significant suppression of semantic processing, but that enough semantic information "leaks" through to generate priming effects or to facilitate the identification of highly familiar stimuli.

Subsequent studies have used ERP recordings to address this problem by measuring the degree of semantic analysis both during and after the AB period (Luck et al., 1996; Vogel et al., 1998). In these studies, semantic processing was operationalized by the amplitude of the N400 component. This electrophysiological response has been shown to provide a sensitive index of the degree to which the evoking stimulus mismatches the current semantic context (Kutas and Hillyard, 1980), with larger amplitude responses for semantically incongruous stimuli. Because the target word must be identified before semantic incongruity can be registered, the N400 response provides direct evidence that a word has undergone semantic processing. Luck et al. (1996) presented semantically incongruous words during and after the AB period, and replicated previous observations that the report of these target words was strongly impaired during the AB period. The key finding, however, was that the amplitude of the N400 response to these words was equivalent inside and outside of the AB period. Thus, even though AB interference severely impaired the conscious report of the second target, the semantic processing of the missed items proceeded normally. In addition, Vogel et al. (1998) found that the amplitude of the P1 component evoked by these stimuli—previously demonstrated to provide a sensitive index of early perceptual processing (e.g. Mangun and Hillyard, 1991)—was also unaffected by AB interference. These results suggest that early perceptual processing and in-depth semantic analysis is normal for targets that are missed during the AB. Finally, Vogel et al. (1998) also acquired measurements of the P3 component, which has been argued to index the process of updating new representations within working memory (Donchin, 1981). This component was completely suppressed during the AB period, consistent with the behavioral observations that the target words were unavailable for conscious report.

To summarize, these ERP studies provide one demonstration of how attention can operate at a relatively late stage of processing, to determine which stimuli will gain access to working memory after the completion of early perceptual and semantic processing. As such, these data highlight an important interaction between top-down attentional control and working memory, where severe capacity limits in working memory are accommodated by goal-driven selection prior to the entry of information into that system.

Attentional selection within working memory

While the attention blink paradigm has sometimes been characterized as a form of "time-based" attention (because processing is curtailed over a specific temporal window), evidence suggestive of postperceptual selection has also been generated with a paradigm that measures object-based attention. Duncan (1984) introduced an influential procedure for measuring object-based selection. In these experiments, observers reported the properties from two briefly presented objects that were superimposed in space. One object was a rectangular box that varied in height and in the placement of a gap on the right or left. The other object was a line that varied in orientation and texture. Duncan observed that the accuracy of subjects' reports was best when they reported two attributes from one object (the within-object condition), rather than one attribute from each object (the between-object condition). Because this procedure controlled for the spatial separation between the judged features and the number of judgments required, Duncan argued that the limits of visual processing are best defined in terms of the number of object files that must be attended.

An interesting question regarding this effect, however, concerns the specific stages of processing that are influenced by object-based selection. Is the advantage for the within-object condition realized during the initial sensory analysis of the stimuli, or during later stages of processing? Awh et al. (2001) investigated this question using a similar procedure. In this case, subjects viewed displays that contained two separate lines that differed in terms of both color and orientation. After each presentation, they reported either the texture and gap position of a single line, or they reported the texture of one line and the gap position of the other line. This procedure replicated Duncan's initial observations. Performance was better in the within-object condition than in the between-object condition. The key result, however, was that this pattern of results was also observed when the relevant objects (i.e. the specific stimuli from which to report each attribute) were not cued until *after* the objects had been masked. Given that the perceptual analysis of these simple line drawings was likely to have been completed by the time of mask offset (i.e. 282 ms after target onset), these data suggest that object-based selection in this procedure was occurring during a post-perceptual stage of processing. Awh et al. (2001) suggested that the within vs. between-object manipulation may influence the relative quality of representations within visual working memory. Luck and Vogel (1997) provided evidence that representations in visual working memory take the form of integrated object files. Thus, a process of post-perceptual selection between the two objects may provide an explanation for the decline in performance during the between object condition. While subjects directed attention toward the internal representation of the first object, the quality of the second object's representation in working memory may have declined. This cost may not have been incurred in the within-object condition, because only one integrated object representation had to be attended. Consistent with this analysis, it was only the second reported attribute that showed the within-object advantage—an interaction with order-of-report that was also clear in Duncan's original study. By this view, the Duncan (1984) paradigm illustrates another mode of interaction between attention and working memory. In this case, the integrity of the representations within working memory was determined by internal shifts of attention toward one object or the other.

Attention-based rehearsal in working memory

In the last section we hypothesized that the object-based selection effects in Duncan's (1984) procedure may have been due to the internal allocation of attention toward representations in working memory. Indeed, the notion that attention can influence the integrity of representations in working memory has been under active investigation for some time. In particular, much of this work has focused on a hypothesis that was first proposed by Smyth and Scholey (1994). These authors suggested that covert shifts of spatial attention could aid in the maintenance of information in spatial working memory, in much the same way that covert articulation has been shown to participate in the maintenance of information within phonological working memory (Baddeley and Hitch, 1974). Below, we review three types of evidence that have supported the idea of attention-based rehearsal in working memory.

First, a broad survey of the neural substrates that mediate spatial working memory and spatial selective attention show a striking degree of overlap (Awh and Jonides, 1998). Both processes appear to recruit a right-hemisphere dominant set of frontal and parietal brain regions, as revealed by unit-recording studies in nonhuman primates, neuropsychological evidence, and neuroimaging studies with human subjects. Furthermore, targeted comparisons between these processes have also provided support for the hypothesis that there is considerable anatomical overlap between the two (e.g. Chelazzi and Corbetta, 2000; Corbetta et al., 2002). Thus, the hypothesis of attention-based rehearsal draws some support from the degree of overlap between the neural systems that are presumed to mediate spatial attention and spatial working memory. This kind of correlational evidence has limited inferential power, however, because it does not entail a true functional relationship between one process and the other. For example, these data in isolation leave open the possibility that shifts of spatial attention merely tend to accompany tasks in which spatial locations are highly relevant.

One particularly noteworthy instance of overlap between selective attention and working memory comes from a study of activity within the lateral intraparietal sulcus (LIP). Bisley and Goldberg (2003) provided a powerful demonstration of how neurons within LIP mediate performance during a task in which monkey had to plan a saccade to a remembered location. During the time that the monkeys held a specific saccade target in mind, they observed delay period activity within LIP neurons whose receptive fields corresponded to the saccade target. In addition, these changes in LIP activity were strongly associated with lowered sensory thresholds at the remembered locations. When irrelevant distractor stimuli were flashed in a location away from the remembered location, there was a temporary disruption of the perceptual advantage at the saccade goal. This change in perceptual performance was accompanied by increases in the firing rate of LIP neurons representing the distractor locations, with little change in the firing rate of LIP neurons that represented the saccade target. These data demonstrate a tight relationship between activity within the LIP, the maintenance of a position-specific memory, and the resulting attentional modulations of visual thresholds (c.f., Sereno et al., 2001; Chafee and Goldman-Rakic, 1998).

The Bisley and Goldberg (2003) results are consistent with one clear prediction of the attention-based rehearsal hypothesis. Specifically, if spatial rehearsal in working memory is accomplished through shifts of attention toward the memorized locations, then the typical consequences of spatial orienting should be apparent at those locations. As we reviewed above, a wide range of methods has demonstrated that visual processing is enhanced at attended relative to unattended locations. Thus, the hypothesis of attention-based rehearsal predicts that the same effects should be apparent at memorized locations. Awh et al. (1998) tested this prediction by measuring reaction times to discriminate a letter-like stimulus that appeared during the delay period of a spatial working memory task. They found that reaction times to this stimulus were significantly faster when the stimulus appeared at the memorized location, compared with when the stimulus appeared elsewhere in the visual display. Using the same displays, it was also determined that this reaction time effect was absent when subjects memorized the identity rather than the location of the same memorandum, suggesting that the RT effects were due to spatial rehearsal rather than some aspect of the stimulus displays.

Functional MRI and ERP studies have also been shown to provide sensitive measures of where spatial attention is oriented. Both techniques reveal amplified visual responses contralateral to attended locations in space. Likewise, both fMRI (Awh et al., 1999; Postle et al., 2004) and ERP studies (Awh et al., 2000; Jha, 2002) have revealed amplified visual responses contralateral to locations that are being held in spatial working memory. Finally, a recent study by Theeuwes et al. (2005) examined eye movement trajectories during a period in which subjects were also maintaining a location in spatial working memory. They found that saccadic trajectories deviated away from the memorized locations, in much the same way that saccadic trajectories deviate away from real visual stimuli (Godjin and Theeuwes, 2002; Sheliga et al., 1994). These data suggest a connection between spatial working memory and the oculomotor system that may derive from the tight linkages that have been proposed between the oculomotor system and spatial attention. Overall, this broad array of studies converges on the conclusion that that which is remembered is also attended. Furthermore these data demonstrate that spatial rehearsal elicits the same kind of covert attentional shifts that modulate some of the earliest stages of visual processing.

Clear evidence that attention moves toward the locations held in spatial working memory, however, does not provide clear evidence that attention plays a functional role in the maintenance of spatial memories. Just as in the case of the anatomical overlap that has been observed in studies of memory and attention, it could be that this strong correlation between attentional shifts and memory locations is epiphenomenal to the core processes that maintain information in spatial working memory. In order to provide stronger evidence that these shifts of attention facilitate the maintenance of information in working memory, it is necessary to show that when these shifts are prevented or interrupted, memory performance declines. Smyth and Scholey (1994) showed just such an effect by measuring subjects' ability to remember the temporal order of a set of locations within a pre-defined spatial array while they performed various secondary tasks. Across a range of secondary tasks, Smyth and Scholey (1994) demonstrated that serial spatial memory was selectively impaired by those tasks that require shifts of spatial attention away from the memorized locations (see also Smyth, 1996). Likewise, Awh et al. (1998) compared the effects of two secondary tasks that were presented during the delay period of a spatial working memory task. When the color discrimination task required shifts of attention away from the memorized locations, memory accuracy declined relative to when an even more difficult color discrimination task did not require such shifts. These results suggest that sustained shifts of attention to the memorized locations play a true beneficial role in the maintenance of information in spatial working memory.

Thus far, the evidence suggests that some form of attention-based rehearsal is likely to contribute to the maintenance of information in spatial working memory. However, this leaves open the natural question of whether a similar relationship between attention and memory is at work in other domains. Here, we will review the evidence from studies of the relationship between object working memory and object-based attention. One challenge for this analysis is that there is controversy regarding the fundamental mechanisms that underlie object-based selection (e.g. Vecera and Farah, 1994; Kramer et al., 1997; Awh et al., 2001). Does object-based selection involve filtering of inputs solely on the basis of object features? Or are these phenomena best understood in terms of spatial selection that is guided by salient objects? This important issue is beyond the scope of this review. Instead, we have included studies that represent a variety of object-based effects, with the broad goal of documenting how representations stored in working memory have influenced performance in a variety of tasks.

If a strong analogy could be drawn between attention-based rehearsal in spatial and object working memory, one could predict that storing an object in working memory should facilitate the processing of that object should it appear in the external world. A number of studies have provided evidence relevant to this prediction. For example, Pashler and Shiu (1999) cued subjects to form a mental image just prior to the onset of a sequence of pictures. The instructions to the observers were to form a clear mental image, but then to let go of the image and focus on identifying a target digit that would appear in the picture sequence. On half of the trials, an example of this critical image appeared prior to the onset of the target digit; on the other half of the trials, the critical image appeared after the target digit had been presented. Consistent with prior demonstrations of the AB effect, subjects' ability to perceive the target digit was impaired when the critical picture appeared prior to the digit. Pashler and Shiu (1999) asserted that the formation of the mental image—a process that we take to be equivalent to storage in working memory (Baddeley, 1986)—caused the subsequent presentations of that image to capture attention. Downing (2000) reported a related finding. Subjects in his experiment were asked to remember an object over a delay of 3.5 s. During the delay period, two objects were presented on either side of the fixation point, one of which matched the item in working memory. When a secondary probe stimulus appeared on top of the item that was stored in memory, reaction times to the probe stimulus were faster than when the probe appeared over the other object. Again, these results suggest that when an object in the environment matches one that is held (or recently held) within working memory, that object captures the observer's visual attention. One key question, however, is whether these kinds of effects are truly obligatory. If they play a true functional role in the maintenance of object information in working memory, then they should be an inevitable consequence of object rehearsal. In the next section, we discuss evidence relevant to this prediction. To preview the conclusions, there are still important questions regarding the generality of these capture effects.

Working memory and visual search

Visual search paradigms have been one of the dominant methods that have been used to examine the efficiency with which observers can deploy attention to the relevant aspects of a scene. Thus, interactions between visual search and working memory provide an important test bed for understanding the relationship between these systems. Below we review studies that have tested the influence of concurrent working memory loads on performance in visual search tasks. Two main conclusions are emphasized. First, these studies provide an important extension to our discussion of attentional capture by objects held in working memory, by addressing the boundary conditions of this effect. Second, these studies emphasize how the interactions between working memory and attention are determined in part by the kind of information that is relevant in each task.

We have described two studies (Pashler and Shiu, 1999; Downing, 2000) that found attentional capture by objects that were stored in working memory. One important question regarding these results, however, is whether the observed capture effects are *obligatory* or not. That is, does the storage of an object in working memory necessarily lead to attentional capture by subsequent presentations of that object? Two studies cast doubt on this hypothesis. Downing and Dodds (2004) measured visual search performance while subjects were holding an object in working memory that matched a distractor in the search array on half of the trials. If objects that match those in working memory capture attention in an obligatory fashion, then search rates should have been slower when one of the distractors matched the stored item. No such effect was found, however. Woodman and Luck (2002) reported the results of a similar procedure, in which distractors in the search array matched the stored object on half of the trials. In their case, search rates were actually significantly *faster* when the memorized item matched a distractor. It was hypothesized that because the memorized item was never the search target, subjects may have used the memory item to guide attention away from certain distractors. Thus, the data so far suggest that external objects that match the contents of working memory can capture attention, but that this may not be an obligatory phenomenon. How can these conflicting results be reconciled? One possibility is that demand characteristics influenced the experiments that have shown attentional capture from objects that match those in working memory. For example, in the Downing (2000) experiments, subjects could have adopted the voluntary strategy of attending the matching objects first. After all, there was no real penalty for doing so. A similar hypothesis might be raised in the case of the Pashler and Shiu (1999) study, although it should be noted that the investigators explicitly instructed subjects against such strategies (experiment 2). Moreover, in the Pashler and Shiu (1999) study there was a cost—though a modest one—to attending the critical image.

Oh and Kim (2003) offered a different hypothesis regarding the boundary conditions of this phenomenon. Specifically, they noted a common feature of the experiments that failed to see attentional capture by objects that were stored in working memory. In each case, the subjects were engaged in a search task that directed their attention toward a specific target template (Downing and Dodds, 2004; Woodman and Luck, 2002). Because the search task had the highest priority (i.e. the proximal behavioral response was determined by the search task), top-down selection could bias this competitive interaction in favor of the search template (c.f., Desimone and Duncan, 1995), thereby precluding capture effects based on the other object in working memory. Oh and Kim (2003) tested this hypothesis by manipulating the way in which search targets were defined for the observer. In one condition that mirrored those in the previous studies, subjects searched for a specific target shape. In another condition, they searched for any shape that was symmetrical about the vertical axis. Because the latter condition did not indicate a specific target template, they reasoned that there was less opportunity for competitive suppression of the object associated with the working memory task. The results supported this hypothesis. When a specific object served as the search template, search was not slowed by distractors that matched the item in working memory. However, when subjects searched for any object that was symmetrical about the vertical axis, they were significantly slower when a distractor item matched the object stored in working memory. These results suggest that objects stored in working memory can indeed drive attentional capture, but that this effect can be suppressed by competitive interactions within working memory.

The major models of visual search are uniform in ascribing a role for visual working memory in this process (e.g. Bundesen, 1990; Duncan and Humphreys, 1989; Treisman, 1988). If working memory does recruit the same cognitive resources as do visual search tasks, then it seems reasonable to predict that visual search *efficiency* should be impaired by a concurrent load in working memory. Direct examinations of this prediction have produced mixed results. Logan (1978, 1979) found equivalent search rates when subjects were tested with and without a concurrent load in verbal working memory. Woodman et al. (2001) extended these results by examining the effects of a concurrent load in visual working memory—a memory system that may be more directly related to visual search. Although Woodman et al. (2001) found that the memory load added a constant delay to search times, the slope of the search function (i.e. the increase in reaction time as the number of items in the search array increases) was not affected by the load in visual working memory. At first glance, these data may seem to challenge previous proposal that visual search requires the storage of the target template within object working memory (e.g. Bundesen, 1990; Duncan and Humphreys, 1989). When the target template is consistent throughout an experimental session, however, the resulting memory load might be small enough to obscure a clear dual task effect. Consistent with this hypothesis, interference between loads in object working memory and visual search can be seen when the target template for the search is changed on a trial-to-trial basis—a manipulation that is presumed to increase the need for online maintenance of the target template (Woodman, 2003).

Especially when visual search is difficult, there is reason to believe that it entails serial shifts of attention around the search array (Woodman and Luck, 1999). Thus, given the evidence that supports a role for shifts of attention during spatial rehearsal, one could predict that search efficiency should be impaired by a concurrent load in spatial working memory. This prediction has been confirmed in multiple studies. Oh and Kim (2004) and Woodman and Luck (2004) ran independent studies that examined the impact of a spatial working memory load on visual search efficiency. In both cases, even when the target template remained constant throughout the experiment, the efficiency of visual search was significantly impaired by the load in spatial working memory. These data converge with the other studies that found evidence of covert shifts of attention during spatial rehearsal in working memory. In addition, they show that our understanding of the interactions between attention and working memory requires consideration of the functional dissociations between different working memory systems.

Updating and manipulating information in working memory

Of course, virtually every large-scale model of cognition (e.g. ACT-R, Anderson, 1993; EPIC, Meyer and Kieras, 1997) suggests that the key role of working memory is to enable higher level cognitive processes that require a rapidly accessible and easily updated memory system. Thus, an important area of inquiry relates to exactly *how* the information in working memory is updated, accessed, and manipulated. Previous studies have suggested that these so-called "executive" processes may rely on different neural substrates from those that maintain information in working memory (e.g. D'Esposito et al., 1999; Owen et al., 1996; Postle et al., 1999). In this case, it may not be productive to question *whether* attention plays a role in these executive processes, since it is not clear that there are viable alternatives to this broad proposal. However, one important frontier for future research will be to delineate how this kind of attentional processing relates to the other kinds of top-down attentional control that we have already reviewed. For example, Woodman and Vogel (2005) have suggested that there may be independent mechanisms for the maintenance and the consolidation of information in working memory. An interesting question then arises regarding the relationship of these processes to other important executive processes within working memory, such as those that purge information from the system when it is no longer needed, or those that actively manipulate the existing representations within that store.

CONCLUSIONS

We have argued that the interactions between attention and working memory are best understood by considering the variety of ways in which each process is implemented. Selective attention enables the efficient processing of new information during multiple stages of processing including both early sensory and postperceptual processes. At the same time, working memory can be functionally dissociated based on the type of information that is maintained within this online system. Documented interactions between these systems include the role of attention as a "gatekeeper" that determines which items will occupy the limited workspace within working memory. In addition, the same attentional processes that facilitate the early sensory identification of new information are apparently recruited for the active maintenance of information within spatial working memory. While there are important unresolved issues, a similar relationship might apply to the systems that maintain and select object representations. Finally, there is a broadly defined class of "executive" attentional processes that participate in the active manipulation and updating of the contents of working memory. Thus, the relationship between attention and working memory is multifaceted, reflecting the diverse modes of operation within each of these systems. A careful appreciation of these distinctions will facilitate our understanding of the interactions between these core components of cognitive processing.

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